PSR Beam Losses at Injection

R. Macek, 12/9/2004

Outline

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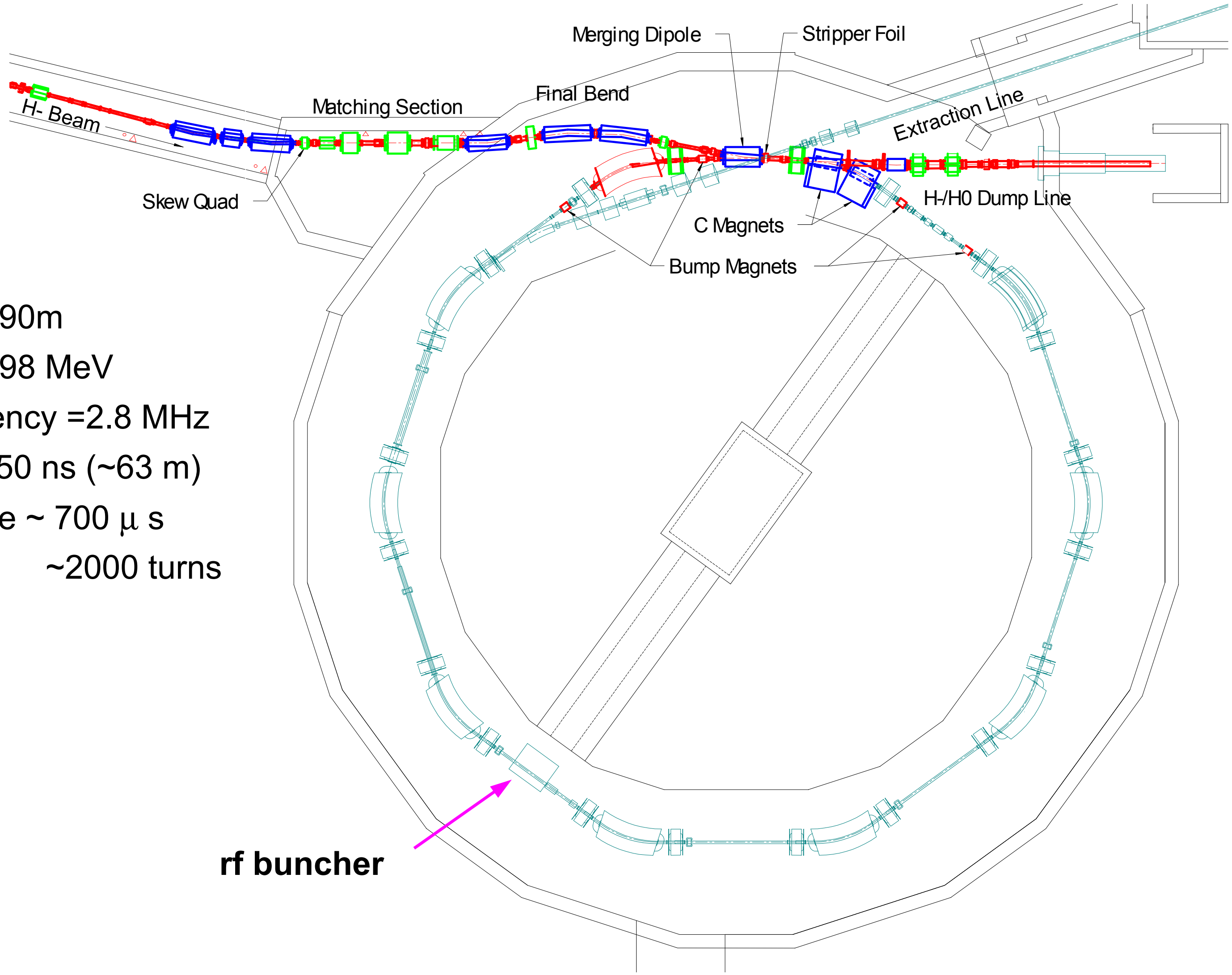
  - PSR Loss Mechanisms
  - PSR Loss Measuring
- Leading loss terms
  - Foil scattering (large angle Coulomb + nuclear)
  - Losses from production of excited states of H0
- PSR experience with stripping foils
- Extra losses at high intensity (space charge)
- Conclusions

PSR Layout



Circumference = 90m

Beam energy = 798 MeV

Revolution frequency =2.8 MHz

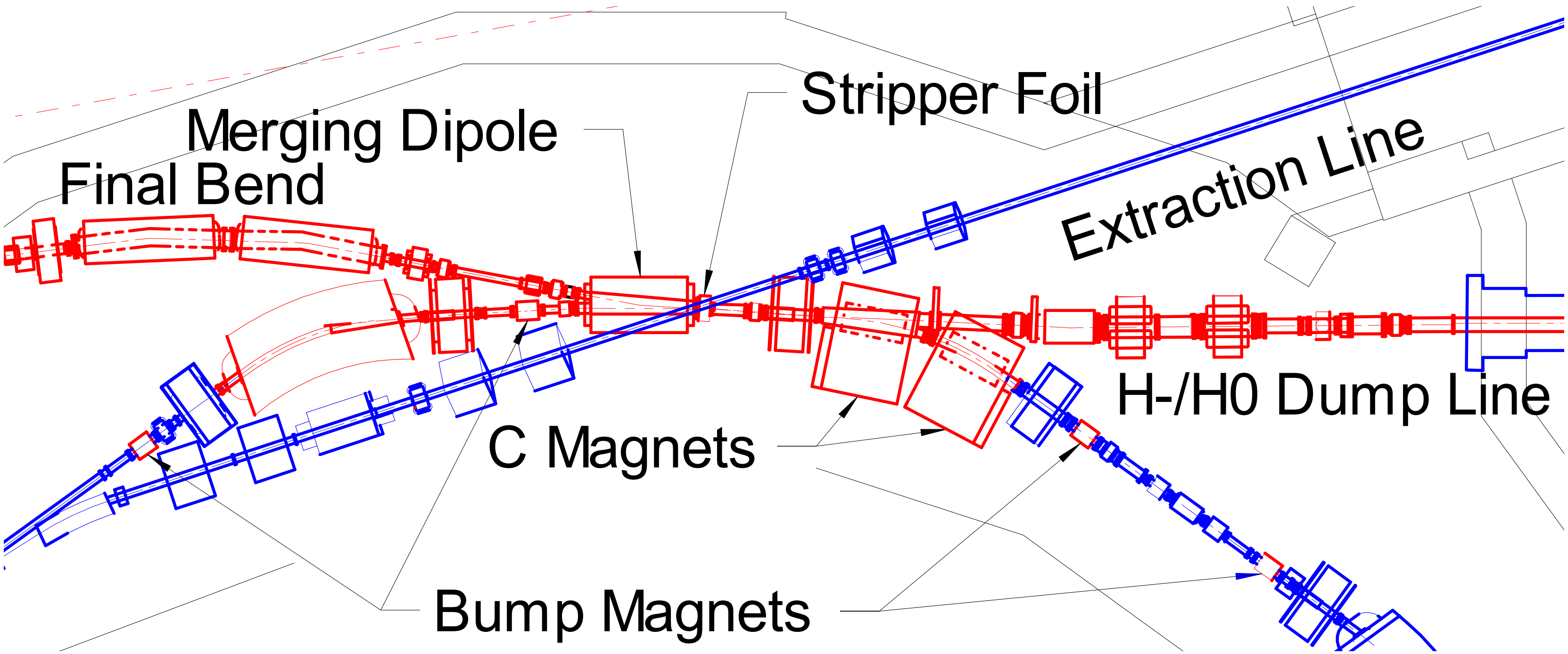
Bunch length ~ 250 ns (~63 m)

Accumulation time ~ 700 μ s

~2000 turns

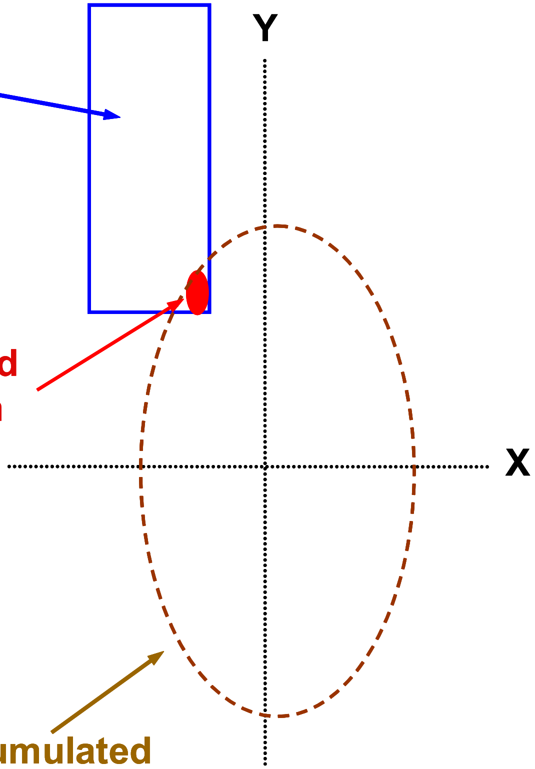
rf buncher

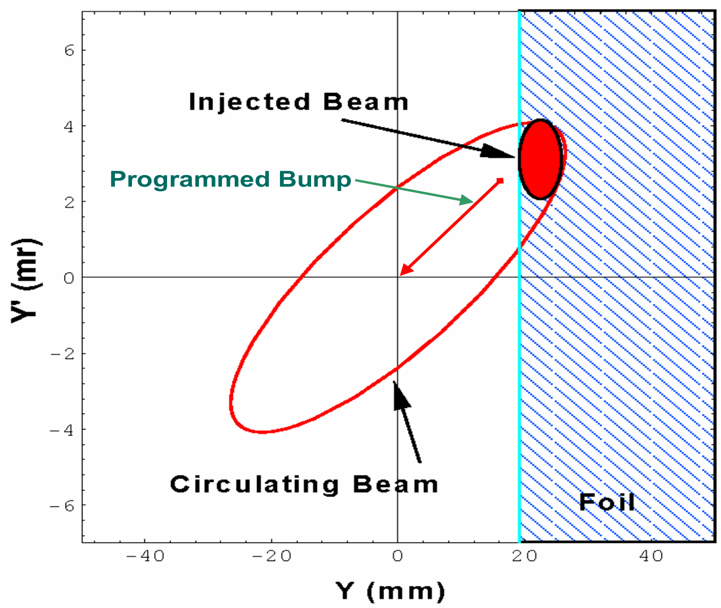
PSR Injection Layout

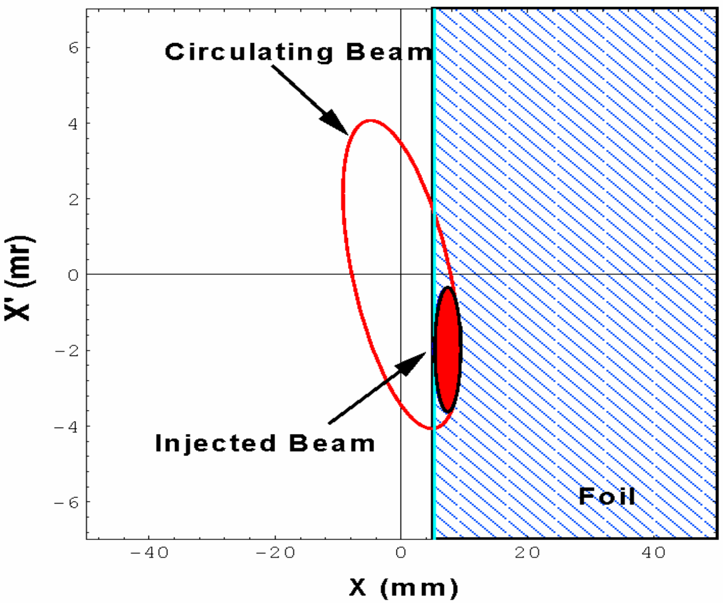


Beams at injection foil

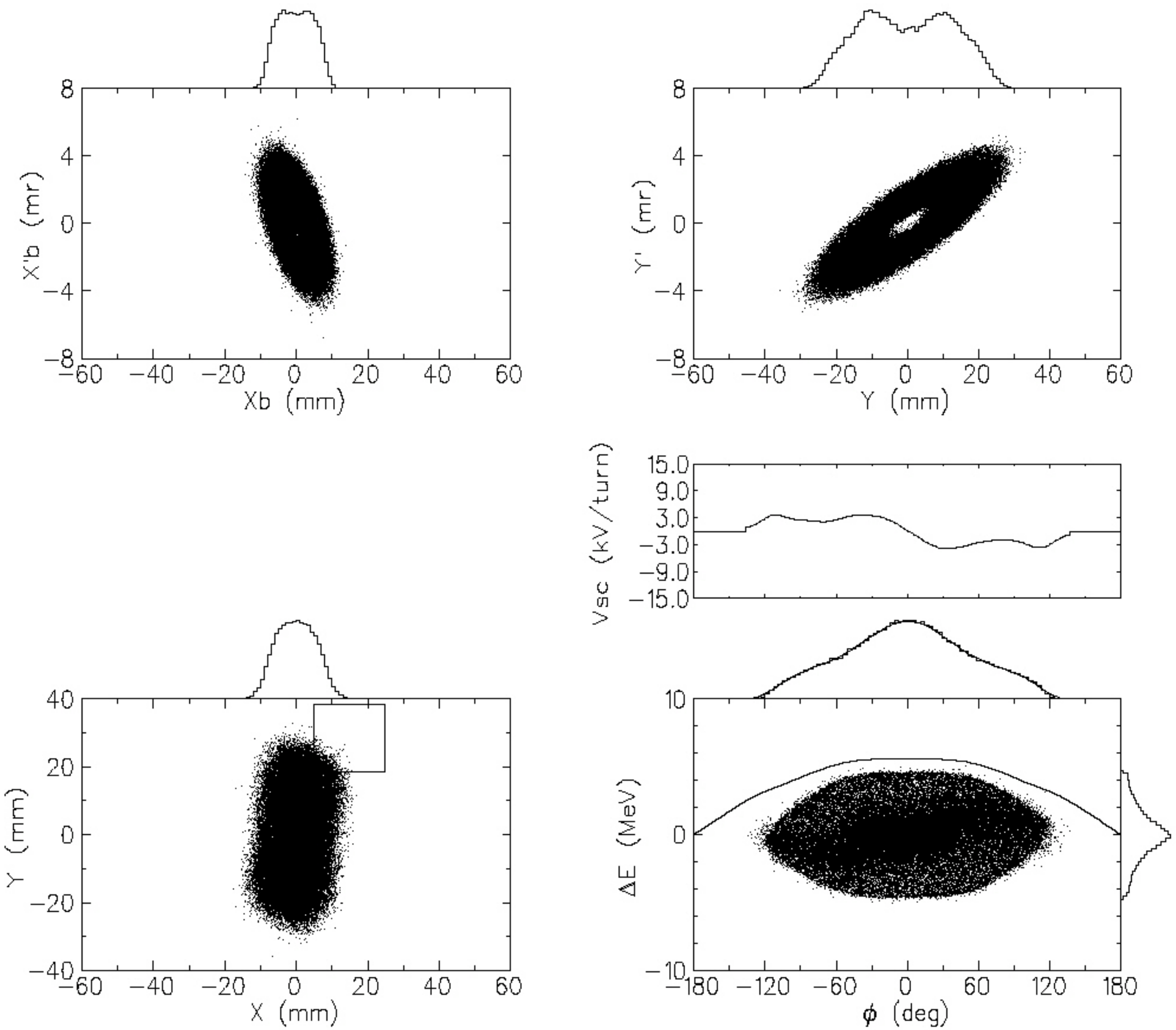
New foil







ACCSIM Output for PSR



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PSR Loss Mechanisms

- **Controlled losses**
  - **H0($n \leq 2$), H- through or missing the foil go to beam dump (2-5%) through large acceptance transport designed to handle the different beams at the same time**
  - **These "losses" are a trade off between stripping efficiency and uncontrolled losses (producing radio-activation)**
- **Uncontrolled losses (~0.15-0.2%) for a good tune at 5-6 μC/pulse**
  - **Scattering in the stripper foil (~65% of total loss)**
    - Large angle, single Coulomb (~35% of total loss)+ plural scattering
    - Nuclear scattering/interactions (~30% of total loss)
  - **Production of excited states of H0(n=3,4,5..) which strip part way through first down-stream dipole and fall outside of the ring acceptance (~15-20%) of total loss after initial foil "shrinkage"**
  - **Extraction losses (<0.03%) (<10-15% of total loss)**
  - **Space charge effects at higher intensity (>6 μC/pulse)**
  - **e-p instability now controlled and not a problem for normal operations**
- **Loss reduction measures**
  - **Reduce foil hits through painting and minimize foil overlap with stored beam**
  - **Foil thickness is tradeoff amongst losses from foil scattering, excited states of H0, and to lesser extent, foil heating**

Loss Measuring at PSR

- **Total losses measured by 19 ion chambers located on tunnel wall opposite each dipole and halfway in between.**
  - **Calibrated by injecting 0.5 μC and letting it all be lost by not extracting**
  - **Uniformity (+-15%) of response checked by spilling locally with closed orbit bumps**
  - **Fast response system (up to ~10 ns) consists of 10 scintillation detectors opposite each dipole**
- **Foil hits from foil current signal**
- **"1st turn losses" (excited states) by storing for ~ 100 μs after end of accumulation and measuring "jump" at end of accumulation**

ΣLM

CM

Loss Monitoring Display

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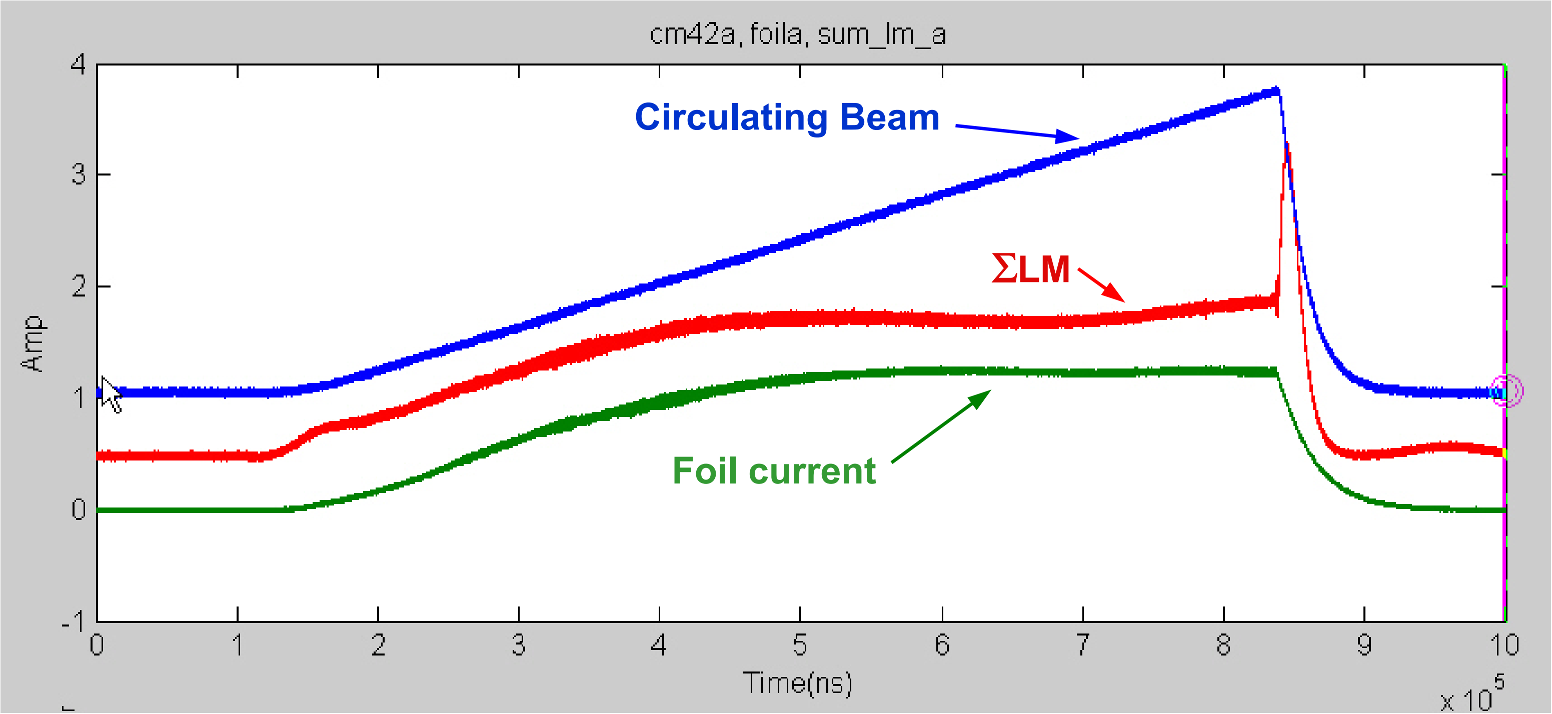
Measuring foil hits

- **Measure current from foil**
  - **Primarily from secondary emission from beam hitting the foil**
  - **Some thermionic emission for higher intensity, long store or foil moved more into beam**



Large angle, single Coulomb scattering

- In thin foils a single scattering of ~100 times or more than rms scattering angle has a significant probability (much greater than from Gaussian approximation)
- Will follow treatment by Jackson in his Electrodynamics book
- Rutherford formula in small angle approximation

$$\frac{d\sigma}{d\Omega} \cong \left(\frac{2Ze^2}{pv}\right)^2 \frac{1}{\theta^4} = \frac{C_0}{\theta^4} \qquad \theta^2 = \theta_x^2 + \theta_y^2 \qquad C_0 = \left(\frac{2Ze^2}{pv}\right)^2 = \left(\frac{2Zm_e r_e}{\gamma\beta^2 M}\right)^2$$

Valid for scattering angles with magnitude between θ_{min} and θ_{max}

$$\theta_{min} \approx \frac{Z^{1/3}}{192}\left(\frac{m_e}{M\beta\gamma}\right) \qquad \theta_{max} \approx \frac{274}{A^{1/3}}\left(\frac{m_e}{M\beta\gamma}\right)$$

θ_{min} set by screening effect in atom and θ_{max} by effect of finite nuclear size

For PSR θ_{min} = 3.3 μrad, θ_{max} = 42 mrad

Atomic Scattering (from Jackson's book)

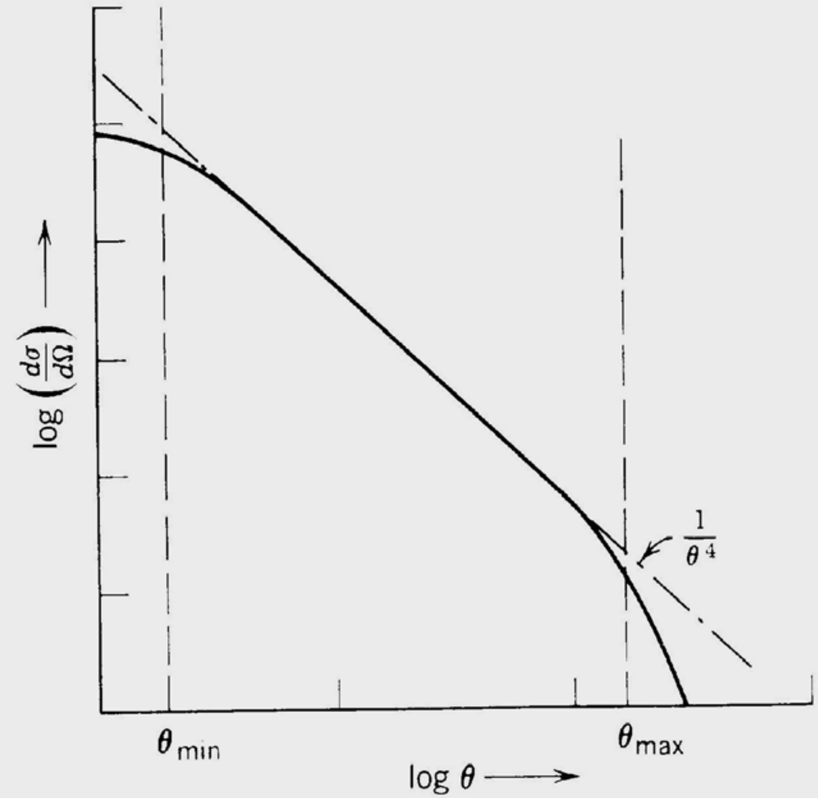


Fig. 13.6 Atomic scattering, including effects of electronic screening at small angles and finite nuclear size at large angles.

Single Coulomb Scattering cont'd(2)

- **Simple model**
  - On-axis, pencil beam hits foil
  - If scattering angle θ_x or θ_y is large enough particle will be lost on an acceptance-limiting aperture
  - Limiting angles, θ_{xl} or θ_{yl} , obtained from limiting apertures, X_A and Y_A

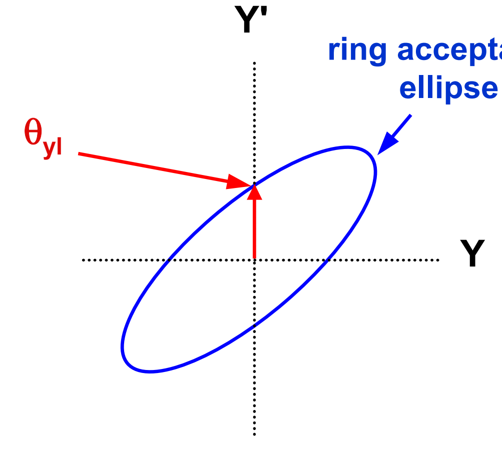
Ring acceptance emittance given by:

$$\varepsilon_{yl} = \frac{Y_A^2}{\beta_{yA}} = \beta_{fy}\theta_{yl}^2$$

Leads to limiting angles:

$$\theta_{xl}^2 = \frac{X_A^2}{\beta_{fx}\beta_{xA}} \quad \text{and} \quad \theta_{yl}^2 = \frac{Y_A^2}{\beta_{fy}\beta_{yA}}$$

At foil

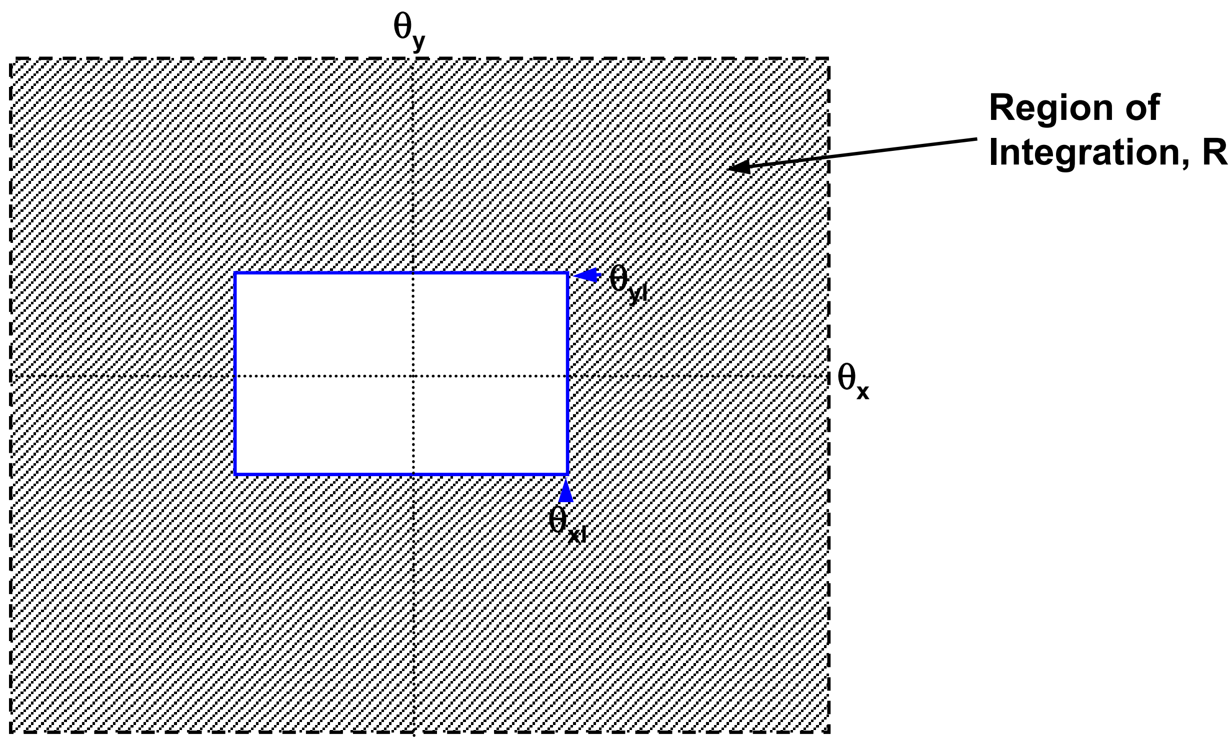


Dynamic aperture in PSR is larger than physical apertures, thus PSR limiting apertures set by septum magnet in X and in Y by a warped vacuum chamber at entrance to SRBM91 leading to $\theta_{xl} \cong$ 6-7 mrad and $\theta_{yl} \cong$ 3 mrad.

Single Coulomb Scattering cont'd (3)

Total cross section for either θ_x or θ_y or both being greater than limiting angles is

$$\sigma_T = C_0 \iint_R \frac{d\theta_x d\theta_y}{\left(\theta_x^2 + \theta_y^2\right)^2} = 4C_0 \left(I + I_1 + I_2\right)$$



Single Coulomb Scattering cont'd (4)

The integrals in σ_T are

$$I=\int_{\theta_{xl}}^{\infty}dx\int_{\theta_{yl}}^{\infty}\frac{dy}{(x^2+y^2)^2},\quad I_1=\int_{\theta_{xl}}^{\infty}dx\int_{0}^{\theta_{yl}}\frac{dy}{(x^2+y^2)^2},\quad I_2=\int_{\theta_{yl}}^{\infty}dy\int_{0}^{\theta_{xl}}\frac{dx}{(x^2+y^2)^2}\quad.$$

Strictly speaking, the upper limits should be θ_{max} instead of infinity but θ_{max} is considerably larger than limiting angles so error is negligible (<2%). The probability of scattering per foil traversal is P=N σ_T t; carrying out the integrations gives

$$P=\left(\frac{2Zm_er_e}{\gamma M\beta^2}\right)^2 N_0\left(\frac{\rho t}{A}\right)\left[\frac{1}{\theta_{xl}\theta_{yl}}+\frac{1}{\theta_{xl}^2}\tan^{-1}\left(\frac{\theta_{yl}}{\theta_{xl}}\right)+\frac{1}{\theta_{yl}^2}\tan^{-1}\left(\frac{\theta_{xl}}{\theta_{yl}}\right)\right]$$

or

$$P=5.674\cdot 10^{-8}\{cm^2\}\left(\frac{Z}{\gamma\beta^2}\right)^2\left(\frac{\rho t}{A}\right)\left[\frac{1}{\theta_{xl}\theta_{yl}}+\frac{1}{\theta_{xl}^2}\tan^{-1}\left(\frac{\theta_{yl}}{\theta_{xl}}\right)+\frac{1}{\theta_{yl}^2}\tan^{-1}\left(\frac{\theta_{xl}}{\theta_{yl}}\right)\right]$$

For PSR P=7.6x10^{-6} per foil traversal. Typically the average protons makes 60-80 traversals of the foil or a probability of 5.3x10-4 (0.053%) of being lost from a single large angle Coulomb scattering.

Refinements on Coulomb scattering calculations

- **To account for finite emittance beam, plural and multiple Coulomb scattering; it probably best to use a simulation code**
  - **PSCAT (H.A. Thiessen, PSR TechNote 85-007)**
    - Simulate using a random number of single scatters distributed according to the cutoff single scattering cross section (Tschalar, NIM B5 (1984) p455)

$$\frac{dN}{d\theta} \propto \frac{\theta}{(\theta^2 + \theta^2_{min})^2}$$

  - **ACCSIM has option that uses plural scattering formulas**
  - **ORBIT has ACCSIM method as an option**
- **ORBIT simulation by Spickermann (using ACCSIM option) for pencil beam in PSR agrees well with analytical calculation shown earlier**

For Proton Driver

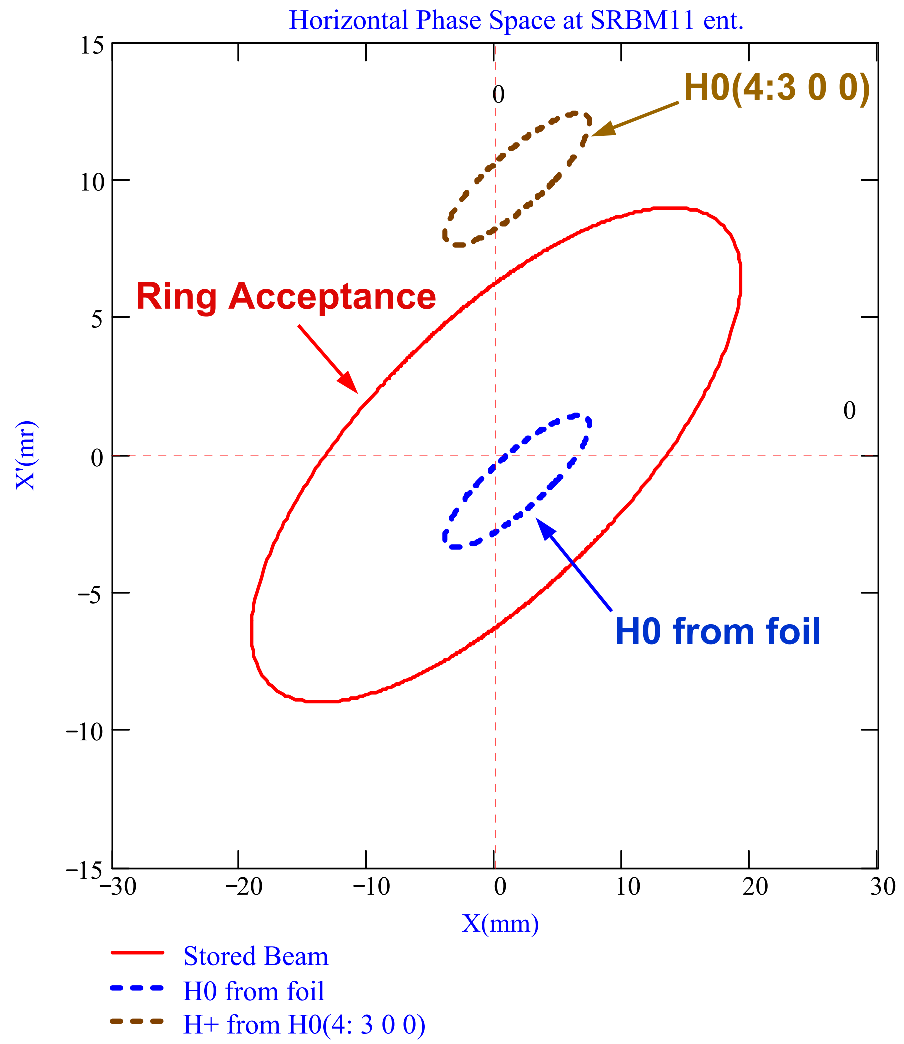
- **Foil: 600 μg/cm^2 carbon foil,**
- **Beta functions at the foil for one possible configuration:**
  - **β_{fx} = 57 m, β_{fy} = 10 m**
- **"Limiting" (acceptance defining) apertures (these need to be clarified):**
  - **Horizontal: dynamic aperture is limiting at ±30 mm and β_{xA} = 57 m**
  - **Vertical: physical aperture is limiting at ±25 mm and β_{yA} = 57 m**
- **Foil hits per injected proton are 4 or 15 depending on scenario.**

Using these, I get θ_{min} = 0.54 μrad and θ_{max} = 6.9 mrad and for the limiting angles, $\theta_{xl} \cong$ 0.5 mrad and $\theta_{yl} \cong$ 1.0 mrad

Thus P $\cong$ 7.5x10^{-6} per foil traversal or loss rate is ~ 3x10^{-5} or 1.1x10^{-4} depending on foil traversal scenario

Example of loss from excited state of H0

- Plot showing horizontal beam phase space ellipses at entrance to first dipole (SRBM11) down stream of stripper foil
  - n=4 Stark state:
    n1=3, n2=0, m=0
  - Strips part way into magnet and resulting H+ has ~ 11 mr wrt H0 from foil and falls outside acceptance of the ring
- n=1 and 2 states are not stripped
- All of n=3, much of n=4 and some of n=5 Stark states are stripped and lost
- Higher Stark states strip and contribute to halo



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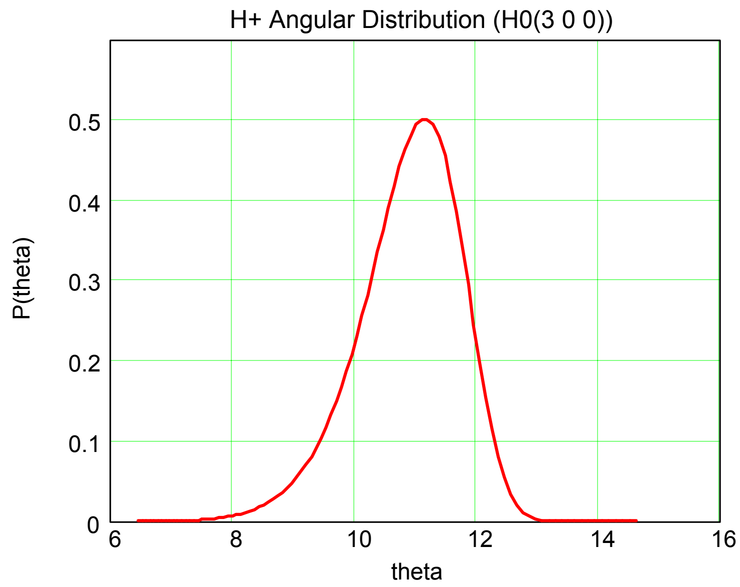
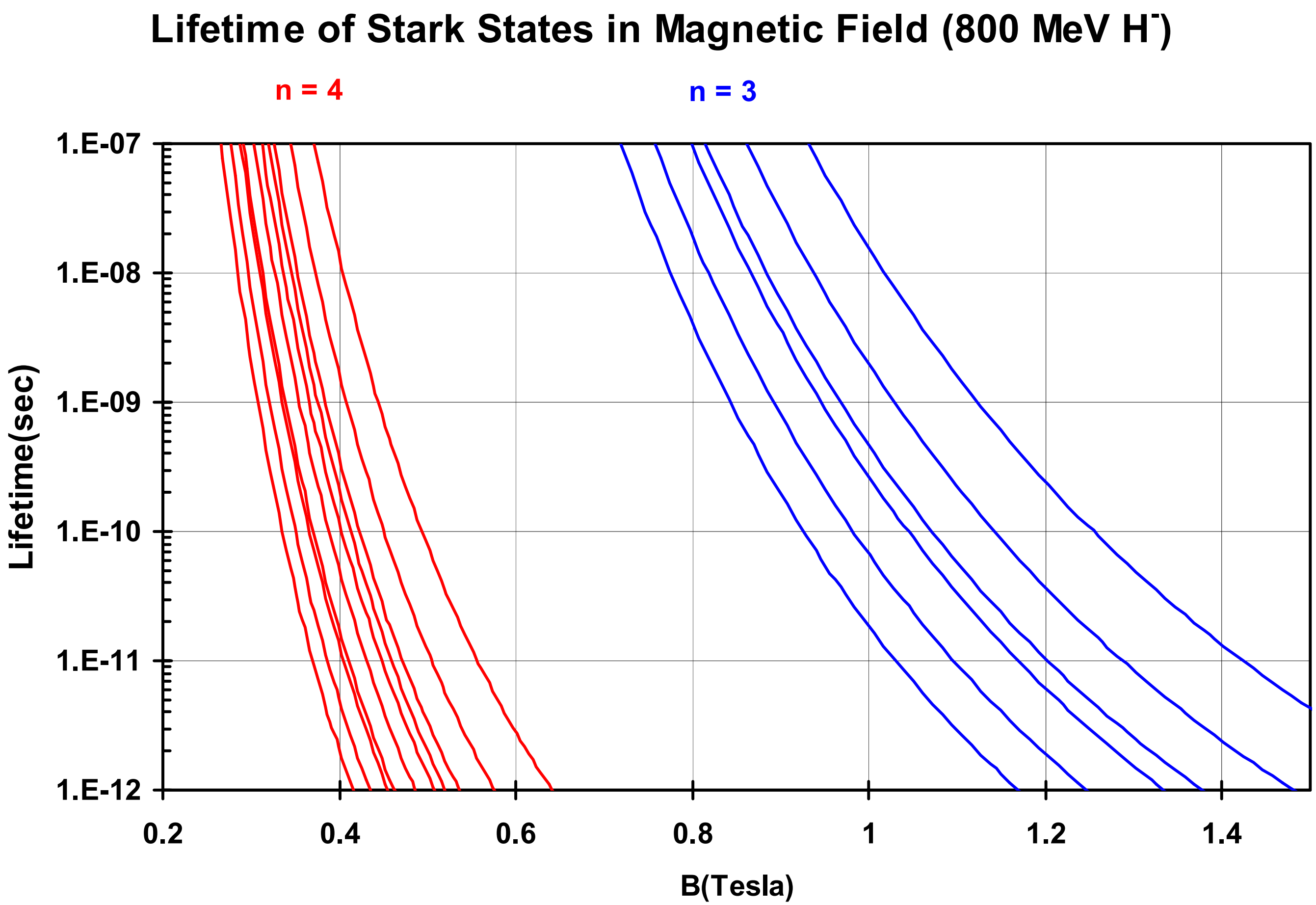
Estimating loss characteristics from H0(n>2)

- Use yield/cross-section data for excited states from HiRab experiments (Gulley etal, Phys Rev A, vol 53 p3201 (1996)) to calculate yield of various excited states for foil in use
  - 1st turn losses for today's PSR in general agreement with HiRab experiments
- Use formulas from Damburg and Kolosov for line width of Stark states and from this stripping probability as a function of magnetic field
  - From these calculate $\Delta\theta$ for the H+ (and width of $\Delta\theta$ band for each Stark state) in fringe field of dipole to see if it falls outside the acceptance
  - Example below for n=4: 3 0 0 state



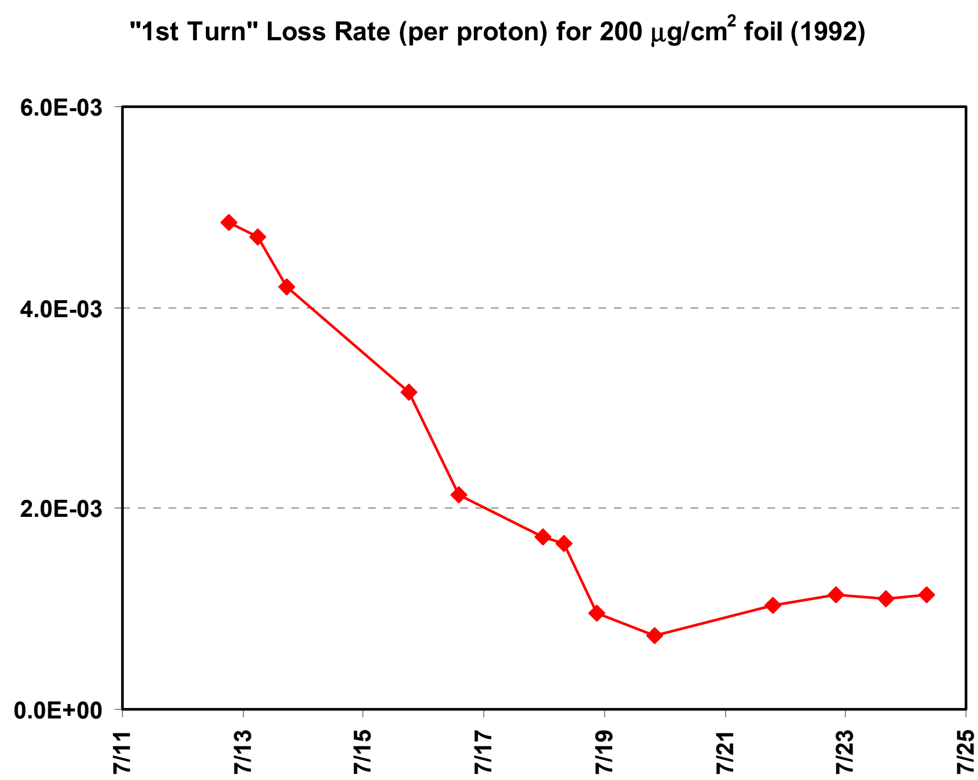
Lifetime of Stark States at PSR

From calculation using Damburg Kolosov formulas



1st turn loss changes with foil "degradation"

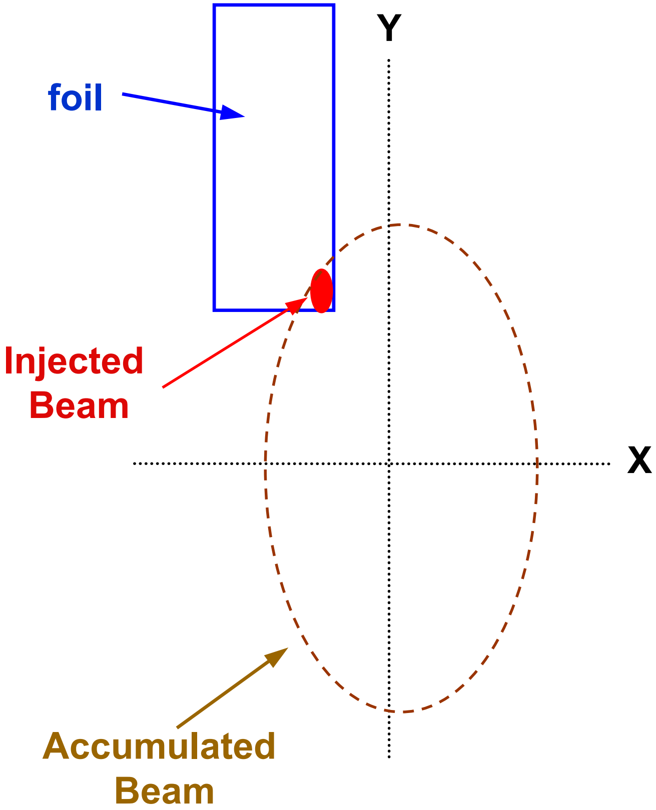
- 1st turn losses change over time foil has been in beam
- Prior to H- upgrade saw large change (factor of ~4) with 200 $\mu g/cm^2$ commercial foil (see graph)
- With direct H- injection and nominal 400 $\mu g/cm^2$ foil (foils made with Sugai process) we see factor of ~2 change in first week of use at production intensities



Foil degradation

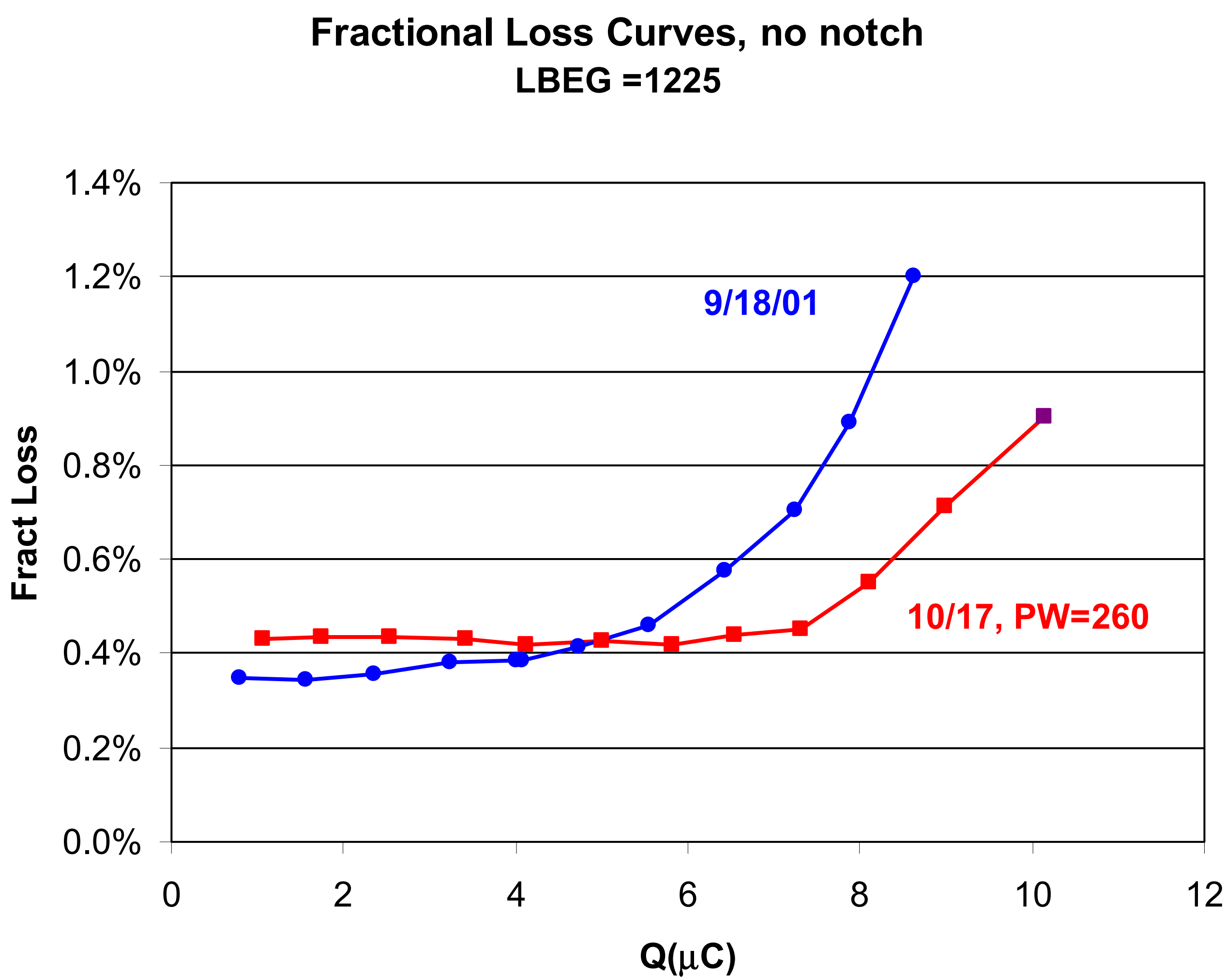
New Foil

Used Foil



Foil edge for stripping distorts with time and becomes thicker leading to fewer excited states

Effect of Space Charge on Losses

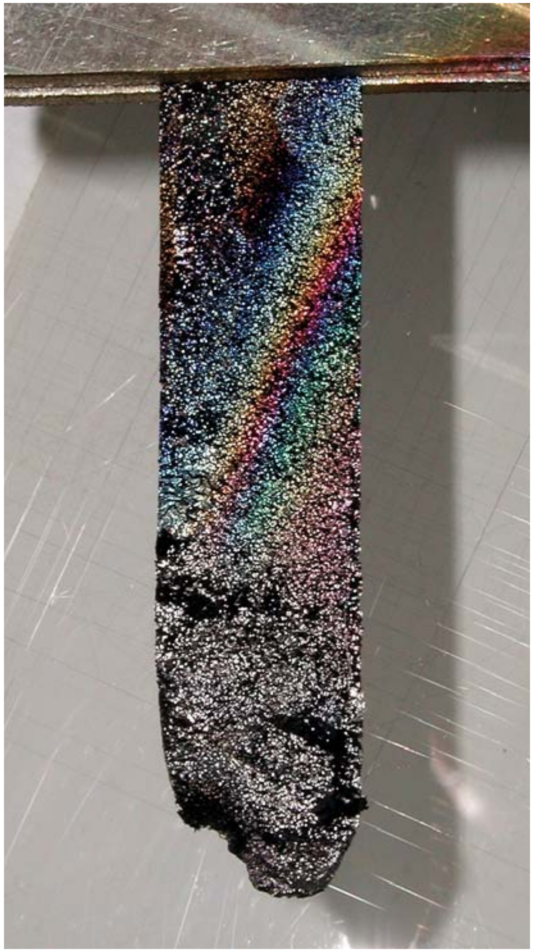


Summary/Conclusions

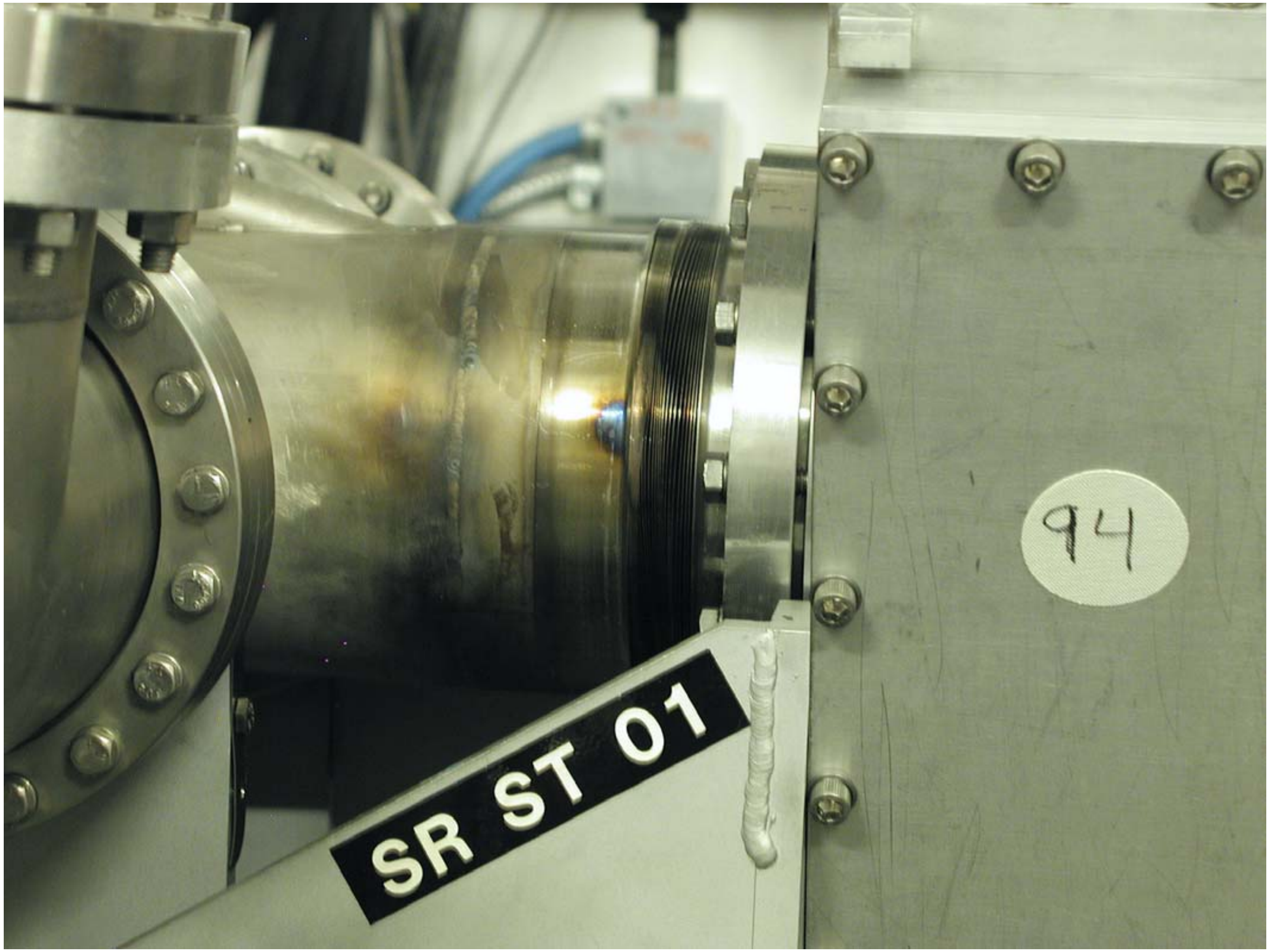
- Beam losses are a major factor limiting beam intensity at PSR
- Foil scattering i.e., large angle Coulomb and nuclear interactions, are the largest (~65%) component of beam loss at PSR
  - More reduction in foils hits is desirable but requires more aperture and/or thinner foil
- Losses from excited states also a significant contributor
  - Need to separate H+ and H0 in lower magnetic field to eliminate losses from n=3, 4 states
    - would require more space in the injection region i.e., a major rebuild of PSR
    - needs to be designed into the lattice from the beginning
- Much effort has gone into developing long-life, minimum area foils resulting in an order of magnitude improvement in life time and lower losses
- Laser stripping could alleviate the foil loss problem but still faces many uncertainties and practical difficulties
- Gas stripping and Lorentz stripping (near quads pole tips) cause occasional loss problems in the H- transport

Backups

More used foil pictures



Burn spot from stripped electrons



Beams at the foil for direct H^- injection